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RECOMMENDATIONS AND EVALUATIONS OF MATERIALS-RESEARCH AREAS OF IMPORTANCE TO MISSILE AND SPACE VEHICLE STRUCTURES

Prepared by Jack B. Esgar, Norris F. Dow, and William R. Micks
in collaboration with the NASA Research Advisory Committee
on Missile and Space Vehicle Structures

NASA Headquarters
Washington, D.C.

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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SUMMARY

This report was prepared to serve as a means of establishing improved communications between structures and materials research communities with regard to the advantages of materials improvements for structural applications.

Several requirements for research on new and improved structural materials are reviewed and discussed. Information about these requirements in terms of the description of the applications and advantages for improved materials is reviewed for high-temperature materials with oxidation resistance and ductility, low-temperature materials with ductility and impermeability, pressure vessel materials, and shielding materials. Statements of needs for information about existing materials are also included. Areas that appear to offer the possibility of significant improvements in materials and where research should be conducted to explore these areas are also discussed.

INTRODUCTION

For some years, the NASA Research Advisory Committee on Missile and Space Vehicle Structures has recognized the need of seeking improved communication and interaction between structures research and materials development communities. This need has been produced by a consideration of structures research problems which frequently result in requirements for new material research, development, or data that appear particularly desirable from the structural standpoint. Proper communication of the desirability of new and specific research and development in materials has lagged for two reasons: first, the simple statement of a need is inadequate to convey a measure by which its importance can be evaluated; second, without a proper evaluation of the difficulty of achieving the desired objective (which can only be made by the materials community), no sensible recommendation towards its achievement can be made. This report was prepared in an attempt to solve the first difficulty, that is, to carry forward to some extent the assessment of gains to be derived from the proposed materials research. The second difficulty was considered to be beyond the scope of the Advisory Committee's charter but nonetheless important. No attempt has been made to compile an all-inclusive list of new or improved materials needs, related information, existing materials information, or to list all areas offering possibilities of materials improvements, but rather to provide a method for such objectives to be achieved through the communication of such needs.

The actual preparation of the report resulted from the efforts of a task group appointed by the Structures Committee Chairman. Comments from all Committee members were solicited, summarized, and presented in a report by Mr. Jack B. Esgar. This summary report was used for a basis of discussion with members of the Advisory Committee on Materials. The present report was prepared on the basis of these reviews and discussions.

Appendix A contains details regarding the method used in making the evaluations of improved materials needs. A list of members of the Committee on Missile and Space Vehicle Structures and members of the task group appointed to investigate the problem areas appears at the front of this report.

I. HIGH-TEMPERATURE MATERIALS, WITH OXIDATION RESISTANCE AND DUCTILITY

A. Recommendations

There is a need for improved materials applicable to the thermal protection of lifting surfaces, leading edges, nose caps, and controls of lifting reentry vehicles. Materials with higher temperature capability, better oxidation resistance, more ductility, and increased fabricability (lower cost) are needed. The magnitude of the gains associated with such material improvements and the time of need are discussed in the following paragraphs.

B. Evaluations

1. The importance of increased temperature capability.- Increased temperature capability of materials would extend the flight corridor of possible lifting reentries. Extending the flight corridor would increase the margin of safety for reentry maneuvers, particularly from superorbital velocities. The relation between temperature capability and reentry-corridor width is shown in figure 1 for the under surface of the wing of a reentry vehicle under "optimum" conditions (absorption of the first, major part of the heat pulses by ablation, followed by rejection of the remaining low-rate part of the pulse by radiation). Greatest gains, evidenced by the steepest slope to the curve, are achieved by temperature capabilities in the 2,800° to 3,200° F temperature range.

Radiation cooling of reentry vehicles, particularly of high L/D vehicles, could be used to a greater degree if high-temperature materials could be used that were oxidation resistant and had enough ductility to permit ready fabrication and to insure reliable structures. Use of such materials would reduce vehicle weights by permitting the removal of the ablation or other active heat-protection materials needed to absorb the first high heating-rate part of the heat pulse. An example to illustrate the degree of potential weight saving is shown in figure 2. (This does not include the effects of possible increases in insulation requirements.) With the present limitations of our booster capabilities, the weight of heat-protection systems has provided a serious limitation on the missions that can be flown. The achievement of lighter vehicles would permit the use of currently available boosters for orbital lifting vehicles, and this could result in the ability to perform lifting reentry vehicle experiments without the delay required for development of increased launch weight capability. The relationship between required launch weight capability and weight of heat-protection system is illustrated in figure 3. Current launch-vehicle capability falls in the shaded band shown in the figure, wherein a reduction in thermal protection weight results in substantial decreases in required launch capability.

2. The importance of increased oxidation resistance.- All refractory metals oxidize rapidly at high temperatures. As operational reentry vehicles are developed, multiflight capability for heat shields and other reentry vehicle structure will become more important. Correspondingly more important becomes the prevention-of-oxidation characteristics of all refractory materials at high temperatures in the atmosphere. Improved oxidation resistant coatings for refractory materials capable of withstanding many reentry temperature cycles need to be developed. In addition, the temperature limits need to be raised for the coatings for the same reason discussed in the previous section.

The merit of achieving re-use capability for reentry thermal protection materials lies primarily in the economy, but there is also increased reliability if the re-use extends to many flights. The potential increase in relative reliability through re-use is illustrated in figure 4.

3. The importance of ductility.- The highest temperature metals, such as tungsten, and refractory ceramic materials which are oxidation resistant, appear desirable for reentry-vehicle components except for their brittleness. Some ductility combined with the refractory properties of ceramics would be advantageous for reentry application. The importance of ductility to reduce weight or increase reliability is illustrated in figure 5. As shown, even 1-percent elongation results in a large benefit.

4. Time of need.- Lifting reentry vehicles are scheduled to be flying in the 1966 to 1967 time period. Accordingly it is already too late to utilize new material developments on the first vehicles. Advances in the areas discussed above are needed in the near future to achieve the benefits described for the second generation, operational lifting reentry vehicles.

5. Possible directions of research emphasis.- Two possible directions for materials-research emphasis which arise from the foregoing evaluation are described under the following two headings:

(a) Refractory Metal with Oxidation Resistance: A possible direction of materials-research emphasis to achieve characteristics identified above as desirable could be in the development of a refractory metal for use in the 3,000° F temperature range, if some inherent oxidation resistance along with adequate structural quality and ease of fabrication could be retained. Considerable research and development has been devoted to refractory metals (molybdenum, niobium, tantalum, and tungsten) for applications to flight vehicles. Progress has been slow in obtaining material of suitable quality and coatings that provide adequate oxidation protection, but it now appears that several combinations of coatings and metal will soon be available for use in the 3,000° F range. The numerous detailed problems that must be solved to achieve long life of fabricated assemblies, however, indicate that a material that requires no coating would greatly simplify design and fabrication problems and increase life and reliability of the structure. Recent efforts to combine a small amount of oxide with chromium metals suggest that such a material will display adequate oxidation resistance in the 3,000° F temperature range and also possess good ductility at room and elevated temperatures.

This type of oxidation-resistant material with 3,000° F capability would be useful for the leading edges and erosion (heat) shields of lifting reentry vehicles. This application would require thin sheet material that can be formed and assembled into structure by riveting or welding. The need is immediate, and the material would be used as soon as it became available.

This material would be useful for lifting reentry vehicles developed in the future as well as the aerospaceplane type of vehicle. Numerous industrial applications involving high temperatures in oxygen atmospheres are also envisioned. The oxidation-resistant metal would, however, contribute particularly to the life and reliability of lifting reentry systems as compared with metals with present-day coatings (and those developed in the foreseeable future) which require careful inspection to establish the integrity of the coating before each use at high temperature. Coating damage due to installation, ground handling, micrometeorite impact, or high-temperature exposure will require replacement. The useful life of the vehicle structure thus will be increased one or more times as much as the nominal increase in life achieved by the resistant material over the coated material.

(b) High-Temperature Coatings: Current molybdenum and columbium alloys are being considered for high-temperature applications on lifting reentry vehicles. The temperature capability of these materials is limited to about 3,000° F at which temperature the coating melts. If a coating good at 3,600° F were developed, the heat-transfer rate to the vehicle could be nearly doubled, yielding much more flexibility in reentry maneuvering performance. At this temperature very nearly the entire vehicle could be thermally protected by reradiation for return from orbital velocities. (See fig. 6.) Even more gain (good superorbital reentry capability) could be obtained with the development of tungsten, tantalum, or some new material (such as a ductile ceramic) or alloy (including oxidation-resistant coatings, if required), which had the required properties at temperatures above 3,600° F.

The development of adequate coatings would also permit the utilization of refractory metals for control devices (flaps, etc.), afterbodies of space vehicles such as Apollo, and boost glide vehicles such as Dyna-Soar.

The ability to utilize metallic structures at such temperatures and thus employ, with only limited modification, familiar design practices for ductile metallic materials would be a major advance. Present coatings are not yet sufficiently reliable, nor have adequate techniques been developed for built-up structures to permit utilizing coated refractory metals in current design. Alternate solutions, if reliable coatings for refractory metals are not avialable, have been proposed but remain unproven. Principal difficulties associated with the alternative use of nonmetallic refractories involve design problems associated with the structural use of brittle materials, and attachment and fabrication problems. Weight penalties for such alternative solutions, as shown in figure 5, are significant.

II. LOW-TEMPERATURE MATERIALS WITH DUCTILITY AND IMPERMEABILITY

A. Recommendations

There is a need for improved materials applicable to the construction of large cryogenic propellant tanks. Materials with higher strength-weight ratios, suitable fracture toughness at cryogenic temperatures, which are impervious to liquid hydrogen and liquid helium are needed. The magnitude of the gains associated with improved materials in this area is discussed in the following paragraphs.

B. Evaluations

1. The importance of increased low-temperature-strength/weight ratio.- Increased low-temperature-strength/weight ratio materials for the cryogenic (liquid hydrogen) tanks that will be used increasingly on upper stages of launch and space vehicles will pay off directly in increased mission capability and reduced launch weight. The importance of this property can be brought out by calculations of possible effects on the manned lunar landing mission. For example, an increase in usable strength-to-weight ratio from 1,000,000 to 2,000,000 inches for the material for the liquid hydrogen tanks of the upper stages of the Saturn-V could make possible the achievement of the manned lunar landing with (a) a large, three-man (5,000-pound) Lunar Ferry, or (b) a direct approach instead of Lunar Orbit Rendezvous using an 8,000-pound (two-man) command module, or (c) the landing of a ton of exploration apparatus along with the men on the moon. Such gains are characteristic of this material improvement because cryogenic tank material applies to critical final stages for which every pound saved permits many pounds of reduction in launch weight.

2. The importance of ductility.- For no application is the importance of ductility more dramatically illustrated than for cryogenic pressure vessels. For example the apparent strength of the all alpha titanium alloy Ti-5Al-2.5Sn, as represented by the "un-notched" curve in figure 7, rises continuously with decreasing temperature, but the utilizable strength falls off below about -325° F as shown by the "notched" curve. Experience has shown that such a decrease in notched strength results in unreliability in burst strength of a cryogenic pressure vessel fabricated from such a material. The importance here is similar to that shown in figure 5 for room-temperature materials but the slope of the curve is greater because of the danger of catastrophic failure in the cryogenic tank.

Catastrophic failure must be avoided; either excessive safety factors must be applied in design or conservative low-strength ductile materials must be used - with resulting increases in weight. The importance of high-strength materials and light weight for cryogenic tanks has already been discussed and evaluated in the previous section.

3. Time of need.- Liquid hydrogen as a propellant is just beginning to come into use with the Centaur and Saturn launch vehicles. The design of the high-energy propulsion stages of these vehicles is far enough advanced so that new materials can not contribute to the current design. Accordingly the need here applies to advanced versions of these vehicles. Thus the time of need is primarily within the next 2-year period when the second generation of these vehicles may be expected to launch larger payloads more economically.

4. Possible directions of research emphasis.- One of the most promising approaches now apparent for substantially increasing the strength-to-density ratio for cryogenic fluid containers is to use the filament winding concept. Material strength-to-density ratios at cryogenic temperatures of approximately 2,000,000 inches are now attainable with glass-reinforced plastics and further gains are foreseeable.

However, a major problem area in this approach is the necessity for decreasing permeability of filament-reinforced plastics at low temperatures. Possible approaches to this problem include the use of loaded resins that cryogenic fluids will not penetrate, use of specially shaped filaments or ribbons to increase the length of the flow path through the container wall, and the use of a suitable liner.

The liner approach seems to hold the greatest potential, but there are serious problems with elastic strain compatibility between the liner and the filament composite at low temperatures, both as a result of different thermal contractions and different modulus-strength combinations. For liners to be compatible with glass-reinforced plastic composites, elastic strain capability on the order of 2 to 3 percent are required.

Two approaches to the liner problem seem worthy of investigation: (1) to develop impermeable liner materials with high elastic strain and (2) develop high-strength, high-modulus fibers (such as boron or carbon). This latter approach would favor fibers having a Young's modulus of approximately 20,000,000 to 40,000,000 psi.

III. PRESSURE-VESSEL MATERIALS WITH INCREASED TENSILE-STRENGTH/DENSITY RATIO AND BUCKLING RESISTANCE

A. Recommendations

There is a need for improved pressure-vessel materials with increased tensile-strength/density ratio and increased buckling resistance for solid-propellant rocket motor cases, propellant tanks, and missile shell structures.

a given load, is proportional only to the square root of the increase in modulus. In view of the difficulty of increasing Young's modulus this is perhaps the least attractive property to attempt to improve.

For more highly loaded (efficient) structures, the buckling efficiency may be increased by increasing the compression yield stress of the material. This is indeed an effective approach provided that the loads to be carried are great enough to permit the high yield stress to be utilized. (Gains in this direction can generally be made by structures of increased complexity, such as sandwich construction.)

The most effective way to increase buckling efficiency is by a reduction in material density, because the efficiency varies inversely with density to the first power (not the square root, as in the case of modulus). Further, this applies to the highly loaded structures as well as lightly loaded structures.

3. Time of need.- The need for improved pressure-vessel materials is immediate and extends indefinitely into the future. New boost vehicles utilizing new propellant tanks are constantly being generated with each new improvement in tank design, so important is the weight efficiency to the performance of the vehicle. Until the actually usable strength/density ratios for pressure-vessel materials exceed about 2,000,000 inches, the Young's modulus/density ratios exceed 2×10^8 inches (by an increase in E), and the material densities are less than 1/2 that of magnesium, the law of diminishing returns will not operate to slow down the translation of the materials gains into gains in vehicle performance. (See fig. 9.)

4. Possible directions for research emphasis.-

(a) For Improvement in Tensile-Strength/Density Ratio: The potential increases in tensile-strength/density ratio through the utilization of high-strength whiskers of fibers in composites are well known and have been known now for a number of years. Progress toward the attainment of these potentials has been steady and in direct proportion to the level of effort expended. Rarely has the goal and the path thereto been better defined for any technological advance. There is no reason to believe that this is not the proper direction for research emphasis.

(b) For Improvement in Buckling Resistance: As has been brought out, the most fruitful way to operate upon the buckling resistance of a material is to decrease its density. So little effort has been expended upon research aimed at density reduction, however, that the best directions for emphasis have not been defined. Rather the status is more appropriate to the suggestion of directions for exploration, such as:

(1) Investigation of techniques for the introduction of oriented voids in metals to yield the equivalent of a foamed metal but with a continuous, load-carrying, grained structure like wood. Possibilities that suggest themselves include: the use of filamentary inclusions which are either hollow to begin with or can be dissolved out during processing to leave essentially straight, directed holes; methods of

These materials should be suitable for a wide range of temperatures, and should have a ratio of ultimate to yield strength of 1.2 or more, and a high ratio of the Young's modulus to density. More important than anything else, they should have a low density. The magnitude of the gains associated with such material improvements and the time of need are discussed in the following paragraphs.

B. Evaluations

1. The importance of tensile-strength/density ratio.- A high percentage of the structure of missiles and space vehicles is designed by tensile loading. The weight of tensile structures varies directly with the tensile-strength/density ratio of the material, but for the greatest mass of applications, with the present advanced state of the art, substantial improvements in strength/density ratio are required to effect appreciable gains in performance. The magnitude of the improvement is shown in figure 8 for a typical launch vehicle. The figure shows that only for decreases in weight of 20 to 40 percent for payloads of the order of 2 to 4 percent of the launch weight are the gains in performance (as measured by design velocity increment) significant. Accordingly the need is for research directed toward the achievement of substantial improvements in strength/density ratio.

Increases in tensile-strength/density ratio become more effective in improving performance when they apply to upper stages rather than launch stages. For upper and payload stages the "growth" factor increases and a pound saved in structural weight can save as much as 500 pounds of launch weight as was shown for cryogenic tanks in the previous section. However, only 1/500 as much material is used in the upper stages as in the launch stages. It may be concluded, therefore, that the need is for (1) any possible improvements in the tensile-strength/density ratio of the special, small quantities of materials for upper-stage applications, and (2) for major improvements in the ratio for the large quantities of materials needed for the launch vehicles.

Because the upper stages are critical, and because small quantities are required, improvements resulting in high material costs per pound are justified for these areas. Clearly, however, costly improvements resulting in only small gains for lower stages are not worthy of comparable attention.

Particularly for the upper stages which are often constructed of minimum-gage materials, decreases in density may be far more important than increases in strength. This point will be amplified in the next section.

2. The importance of buckling resistance.- During launch, especially near burnout when the accelerations are highest, much of the vehicle structure becomes critical in compression. This critical compression phase has resulted in failures, in reductions of performance efficiency in order to limit the accelerations, or in excess weight of structural reinforcement.

For lightly loaded (inefficient) shell structures, buckling resistance may be increased by increasing the Young's modulus of the material. However, the increase in buckling efficiency, that is, weight of material required to carry drawing out spherical voids as produced by foaming, to yield elongated, better load-bearing holes; methods of actually piercing the metal economically in other than through-the-thickness direction.

(2) Development of improved hollow filaments for composites utilizing the high-strength glasses or refractory materials suitable for reinforcement of metals as well as plastics.

IV. SHIELDING MATERIALS FOR ENERGETIC PARTICLES AND METEOROIDS

A. Recommendations

There is a need for more effective materials for shielding against geomagnetically trapped electrons and protons and against solar flare protons encountered in space. There are also needs for improved data on the overall attenuation of such energetic particles (including effects of secondary radiation production), and on the frequency and depth of penetration of meteoroids in various materials in the space environment.

B. Evaluations

1. The importance of improved radiation shielding materials.- The weight of polyethylene shielding required to protect man in space for long missions is shown in figure 10 to be prohibitive. Polyethylene, however, is one of the most effective materials (on a weight basis) for stopping energetic protons. The accomplishment of manned flights to the vicinity of Mars and Venus may have to be delayed until some means are found for reducing these shielding weights.

The shielding problem is just as prohibitive for manned space stations in polar orbit because of the lack of protection from the magnetic field of the Earth near the polar regions. Even more prohibitive is the shielding required at altitudes encountering the Van Allen radiation belts or artificial radiation belts created by nuclear explosions. Until a solution is found to the radiation shielding problem, man in space is in jeopardy except at relatively low orbital altitudes near the equator.

2. The importance of improved meteoroid shielding materials.- The magnitude of the meteoroid hazard in space can not be adequately evaluated at present. Estimates of meteoroid populations vary by orders of magnitude; estimates of depth of penetration of hypervelocity particles also vary substantially. While the preponderance of thinking is on the side that ascribes a need for improved meteoroid shielding materials to the problem, the present evaluation is that the need is rather for better data upon which to base an evaluation.

3. Time of need.- The need for improved radiation shielding materials will not become acute until the 1970's. Shielding of the crew for Project Apollo is not possible within the time and weight limitations of the project; they will simply have to accept the (relatively low) probability of encountering a major

solar flare during their relatively brief excursion to the moon. While no definite plans yet exist for a manned interplanetary mission, it is now evident that such a voyage is increasingly hazardous in direct proportion to its longer duration. When such a flight is scheduled, a more definitive time of need can be assigned. Because of the difficulty of the problem, research leading toward improvements in radiation shielding must be carried on currently.

If a major hazard does exist from meteoroids, it is perhaps a more immediate problem than that of radiation. The probability is great of the establishment in orbit of a large manned space station before the attempt to make a manned planetary flight. Such a space station will be subjected to meteoroid bombardment, and the need to evaluate the severity of the hazard is consequently more urgent. If the planetary mission is considered likely in the early 1970's, the space station is more probable for the late 1960's. Flight times of a year or more are required to gather reasonable statistical data on meteoroid punctures. Accordingly unless these data-gathering flights are launched soon they will be the delaying factor to a manned space station program.

4. Possible directions for research emphasis.- The most hopeful direction at present for reducing proton shield weight is through the application of new superconducting materials which remain superconducting at high current densities in the intense magnetic fields that would provide electromagnetic shielding. From a materials standpoint, therefore, emphasis might be directed toward the development of high-field, high-critical current superconductors capable of production in the quantities needed for shielding large vehicles. Because at present these materials are laboratory curiosities, the main problem to be solved in time may be that of developing techniques for fabricating sufficient quantities of wire of adequate size and quality.

V. OTHER MAJOR MATERIALS PROBLEMS

A. Recommendations

Other major problems in materials include the following:

1. Need for improved techniques for designing with brittle materials, including better theories of fracture mechanics, better evaluations of brittle material properties, and better methods of preventing crack propagation.

2. Need for improved materials, property evaluations thereof, and design application techniques therefore for temperature control of space vehicles.

3. Need for improvement in structural material property evaluations of all kinds including increased standardization of test procedures and representative data for properties under unusual conditions (fatigue at cryogenic temperatures, dynamic behavior under complex stress, hysteretic damping under hard vacuum, etc.).

B. Evaluations

1. The importance of designing with brittle materials.- An alternative to the development of structural materials that are ductile for extreme (high or low) temperature environments is the development of design techniques which permit the successful utilization of available brittle ceramics, metals, and composites. The magnitude of the gains achievable in this area has already been discussed to some extent under Sections A and B preceding. Brittle failures are not confined to the extremes of the temperature conditions encountered, however. Improved knowledge of brittle fracture would lead to the prevention of such catastrophes as the Liberty ship failures in World War II and to the ability to relate the strength of a welded pressure vessel to the notch strength of the parent metal, or some other pertinent characteristic, with some degree of confidence, as well as to the utilization of the wide range of advantageous, other-than-structural properties of ceramics.

2. The importance of materials for temperature control.- Adequate temperature control is vital to the reliable functioning of all missiles and space vehicles. The number of failures that can be attributed to inadequate temperature control is large, perhaps larger than any other single cause. The proportion of the total weight of vehicles that is there simply for controlling temperature (thermal shields, space radiators, cryogenic insulation) is substantial. Although a quantitative assessment of this problem is not attempted here, the implications of temperature control for weight and reliability indicate the importance of materials for use in performing this function.

3. The importance of improved material-property evaluations.- Material properties are continuously being measured. The effort is substantial. The need is recognized. The process could perhaps be made more efficient, however, through increased standardization of test procedures, particularly for the newer regimes of temperature, hard vacuum, etc., for which standards have not become established through years of experience. The importance here is as great as the importance of adequate evaluation of properties of the more standardized kinds. Engineering design can not be carried out witout the input property data. The fact that designs are now required for new and special conditions requires that data be available for these conditions of the same reliability that has been expected of property data obtained from standard tests.

VI. CONCLUDING REMARKS

Recommendations for, and first approximate evaluations of, improvements in structural materials have been made based on surveys of structures research problems by the NASA Research Advisory Committee on Missile and Space Vehicle Structures. While these recommendations and evaluations in themselves measure to a degree some of the relative importance of materials researches, both improved evaluations and studies of the difficulties of achieving recommended improvements are still needed. These additional analyses are appropriate areas for consideration by both the materials and structures community.

National Aeronautics and Space Administration,
Washington, D.C., May 15, 1963.

APPENDIX A

In this appendix, brief descriptions are given of procedures used in the various evaluations of the importance of material improvements. The descriptions are identified by reference to the figures to which they apply. Together with data given upon the figures themselves, and related references, the material given in this appendix is intended to be adequate to show what assumptions and approximations were employed to arrive at the plotted values, in order that the evaluations may be extended or re-evaluated as desired.

Figure 1.- The type of reentry considered is the semiskip type which approaches a maximum range glide and yields a two-part heat pulse like the one shown in figure 4 of reference 1. A family of such heat pulses was derived corresponding to the undershoot boundaries for reentry at various values of maximum acceleration. The heating rates and corridor widths corresponding to these were approximated from equations (34) and (A15) and the appropriate figures of reference 2.

Figure 2.- For a blunt, lifting reentry body like the Apollo vehicle, the ablation heat-shield weight is assumed to be 16 percent of the gross weight. The amount of this ablative material could be reduced in increments as the allowable surface temperature of the supporting material increases, as follows:

(1) Above 2,750° F the material over the blunt face that is away from the stagnation point required to take the low-heating-rate part of the heat pulse can be removed.

(2) Above 2,900° F all the material over the afterbody can be removed.

(3) Above 4,000° F the material near the stagnation point required for the low-heating-rate part of the heat pulse can be removed.

These temperature values were taken from heat pulses drawn from typical maximum range, glide reentries.

The curve of figure 2 was faired through points corresponding to the weights calculated removable in the above three stages.

Figure 3.- A lifting reentry vehicle is assumed to have a weight of fixed equipment plus a payload of 5,000 pounds. The weight of structure and all other components proportional to the gross weight of the vehicle are assumed to be 35 percent of the gross weight. With these assumptions, an equation can be written for the gross weight as:

$$W_{Gross} = \left(\frac{W_{Ht.pro.}}{W_{Gross}}\right)W_{Gross} + 0.35W_{Gross} + 5000$$

where

$$W_{Gross} = \text{Gross weight, lb}$$

$$W_{Ht.pro.} = \text{Weight of heat protection, lb}$$

This equation was used to generate the curve of figure 3.

Figure 4.- The assumption is made, consistent with failure-rate data for many components (for example, ref. 3), that the number of failures encountered is inversely proportional to the number of hours of operation. Then if the vehicle has, for example, an expected reliability of 98 percent, in n flights with n vehicles, the reliability is 0.98^n. With re-use of one vehicle, on the other hand, the reliability is

$$1 - 0.02\left(\frac{1}{1} + \frac{1}{2} + \ .\ .\ .\ \frac{1}{n}\right)$$

The ratio of these reliabilities is plotted as the curve in figure 4.

Figure 5.- It is assumed that reliability of a member under tensile loading is a function of the ratio of design strain to ultimate strain. For example, a material having an elongation of 10 percent, an ultimate strength of 70 ksi, and a Young's modulus of 10,500 ksi would have a ratio of design to ultimate strain of 1/24 for a safety factor of 1.5. In order to maintain a constant value of reliability when the elongation is reduced, the design stress is reduced accordingly, being 1/24 of the ultimate elongation times Young's modulus. Weights are assumed to be inversely proportional to these design stresses to give the curve of figure 5.

Figure 6.- Figure 6 is taken directly from reference 4.

Figure 7.- Figure 7 is taken from reference 5.

Figure 8.- Figure 8 is taken from reference 6.

Figure 9.- With the weights and specific impulses given in reference 7 for the Lunar Orbit Rendezvous approach to lunar landing, the influence of changes in material properties on payload capabilities was calculated as follows:

(1) Weight saved in Lunar Excursion Module (LEM) structure was assumed applicable to increase payload in proportion to the ratio of original payload weight (2,000 lb) to the sum of the original payload plus weight saved.

(2) Weight saved in structure on Command Module (C/M) and Service Module (S/M) was calculated to reduce fuel required for midcourse correction on the return to Earth and for injection into the Earth return trajectory from lunar orbit. All other fuel weights were assumed constant, and the LEM gross weight was assumed constant. Ten percent of the savings in gross weight of C/M and S/M was converted into lunar landing payload increases.

(3) In the calculation of the effect of reduction in material density, the weight of all structure was reduced in proportion to the density decrease. Joint design, however, was assumed to require an increasing percentage of structure weight as density decreased, varying from 10 percent at the original material density linearly to 50 percent for material of one-fifth the original density.

(4) In the calculation of the effect of modulus/density ratio, 2,000 pounds of C/M structure was assumed inversely proportional in weight to $\sqrt{E}/\rho$. All other structure was assumed unchanged by changes in E/ρ.

(5) In the calculation of the effect of tensile-strength/density ratio, 3,000 pounds of C/M and S/M structure and 2,100 pounds of LEM structure were assumed designed by tensile loads. Of this structure, 50 percent was also assumed limited by minimum practical material thickness whenever σ/ρ exceeded 2,000,000 inches. The same type of allowance for joints was made as in (3) above with 20 percent of the weight in the joints at $\sigma/\rho = 2{,}000{,}000$ inches. Because of the minimum-gage restriction above this stress-density ratio, the relative joint-weight increase above 2,000,000 inches was reduced reaching a maximum of only 25 percent of the total structure weight at $\sigma/\rho = 3{,}000{,}000$ inches.

Figure 10.- Figure 10 is taken directly from reference 8.

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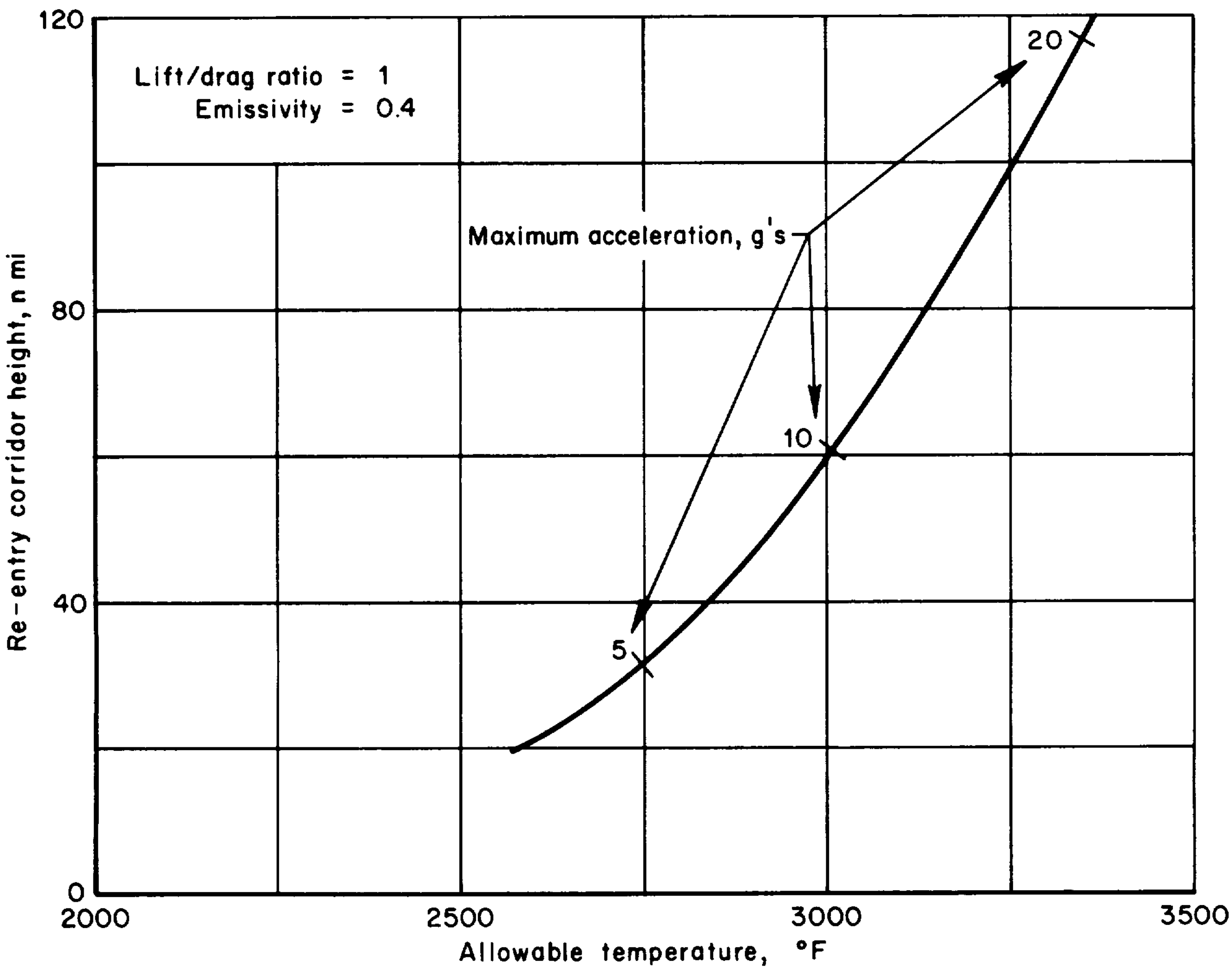

Figure 1.- Effect on height of reentry corridor of increase of allowable lower surface temperature for lifting vehicle reentering the Earth's atmosphere at escape velocity with ablative material to absorb first heat pulse.

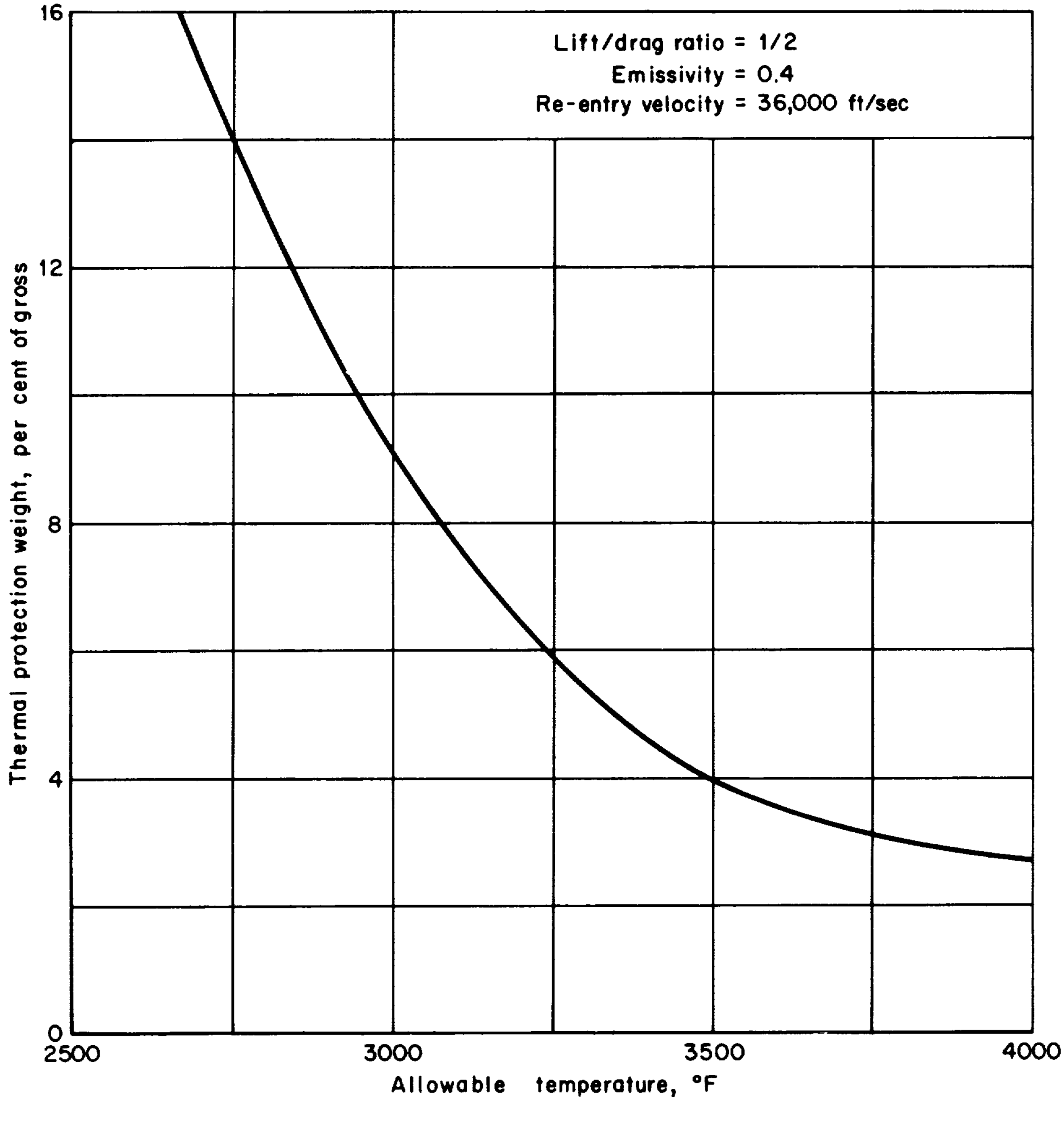

Figure 2.- Reduction in weight of an Apollo-like vehicle by increase in allowable surface temperature to permit increased heat rejection by reradiation, and hence a decrease in ablative material.

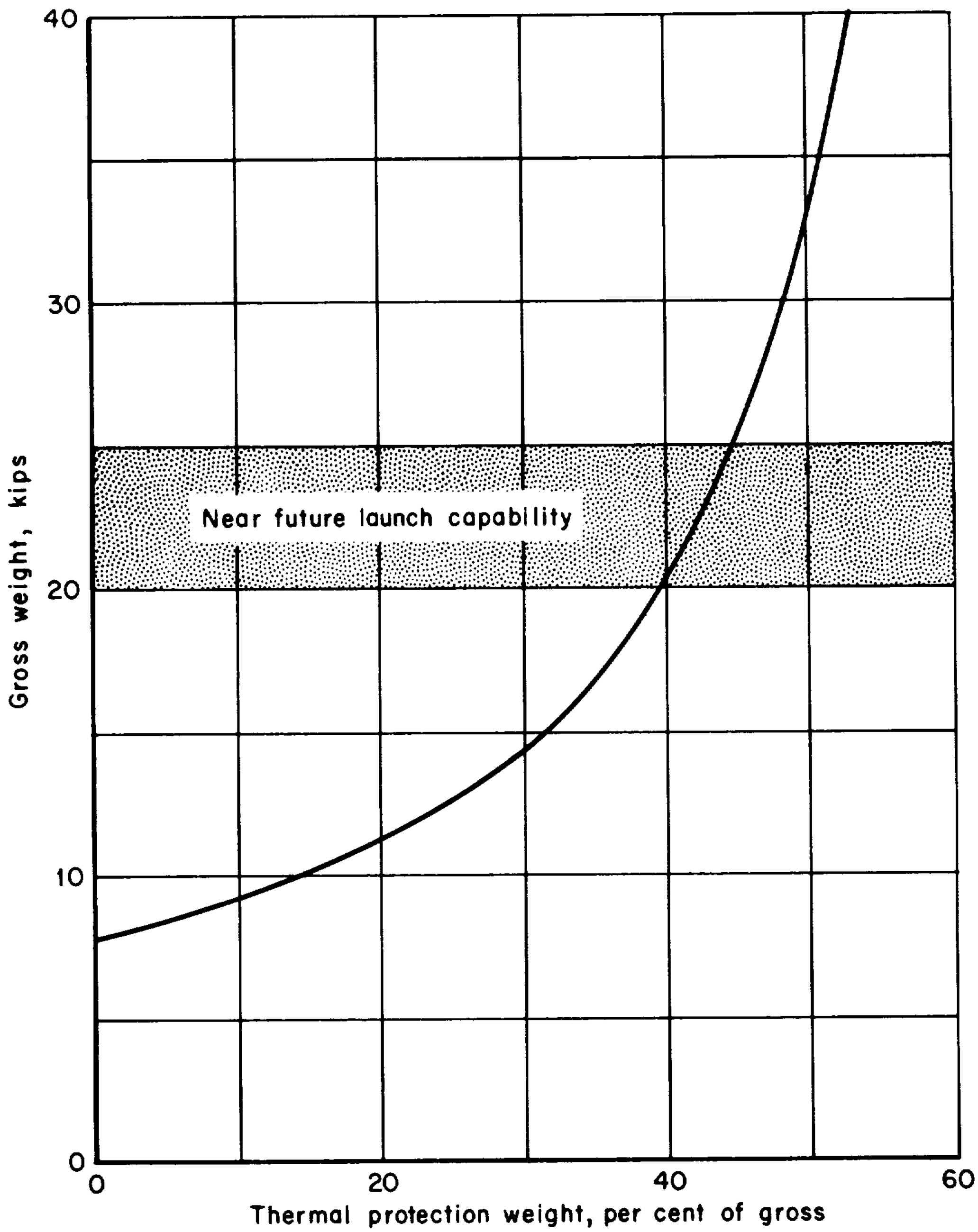

Figure 3.- Effect of thermal protection weight on gross weight of lifting reentry vehicle to carry a fixed weight of 5,000 pounds (equipment and payload).

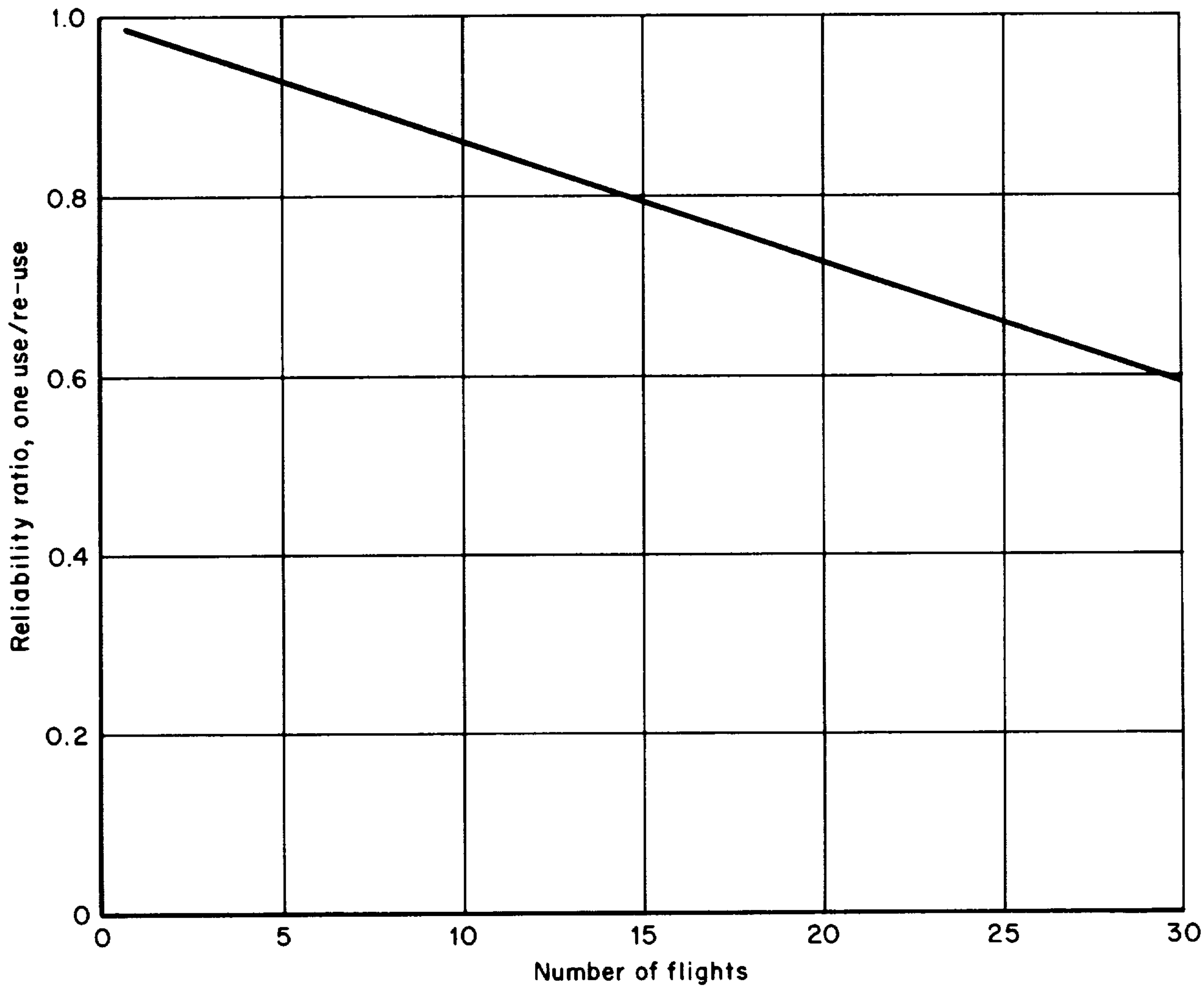

Figure 4.- Potential improvement in reliability possible through re-use for a vehicle with a basic reliability of 98 percent. No allowance made for degradation or damage in flight.

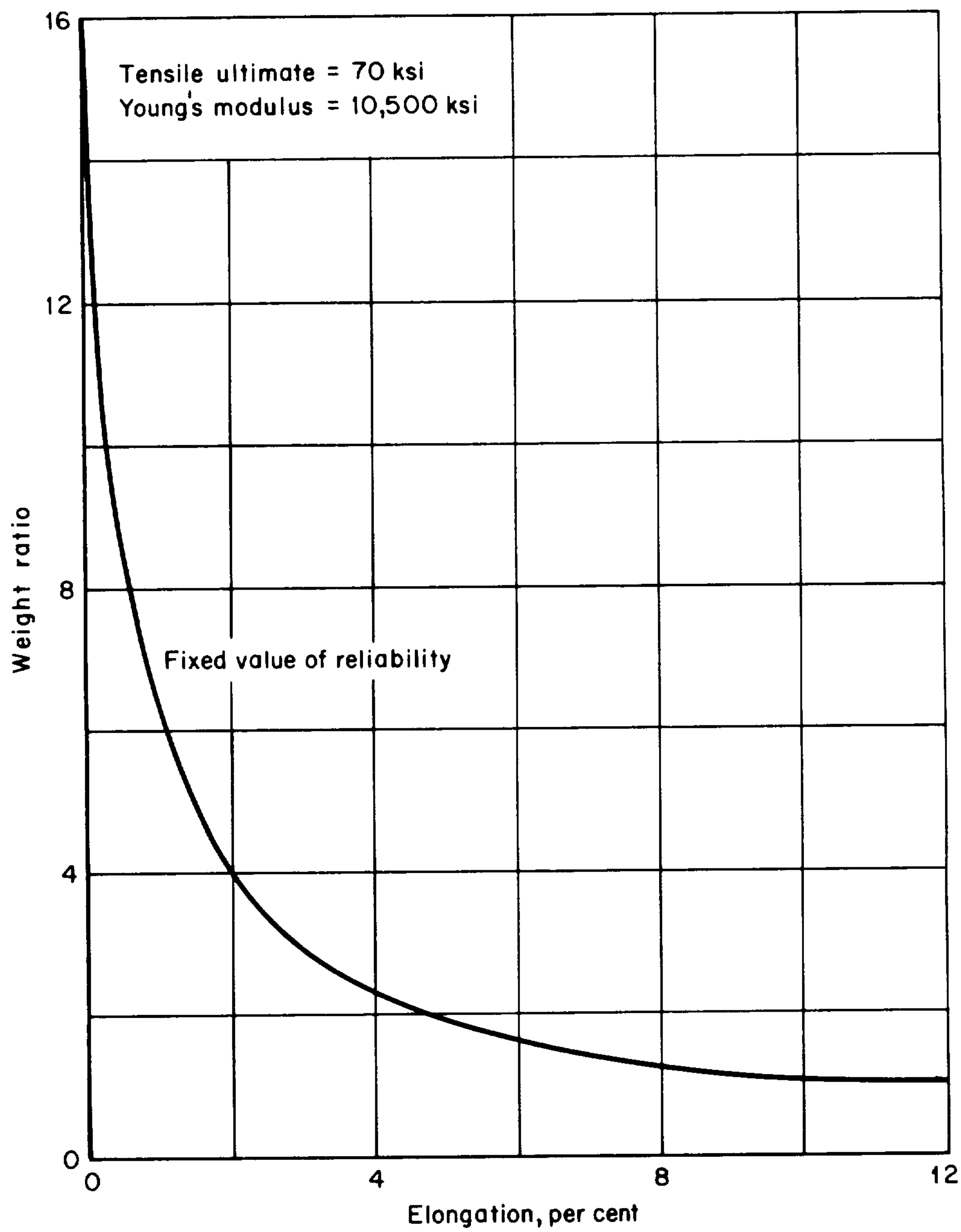

Figure 5.- Weight penalty associated with lack of ductility; curve shows ratio of structure weight to that for a material with an elongation of 10 percent to achieve a constant reliability under tensile loading.

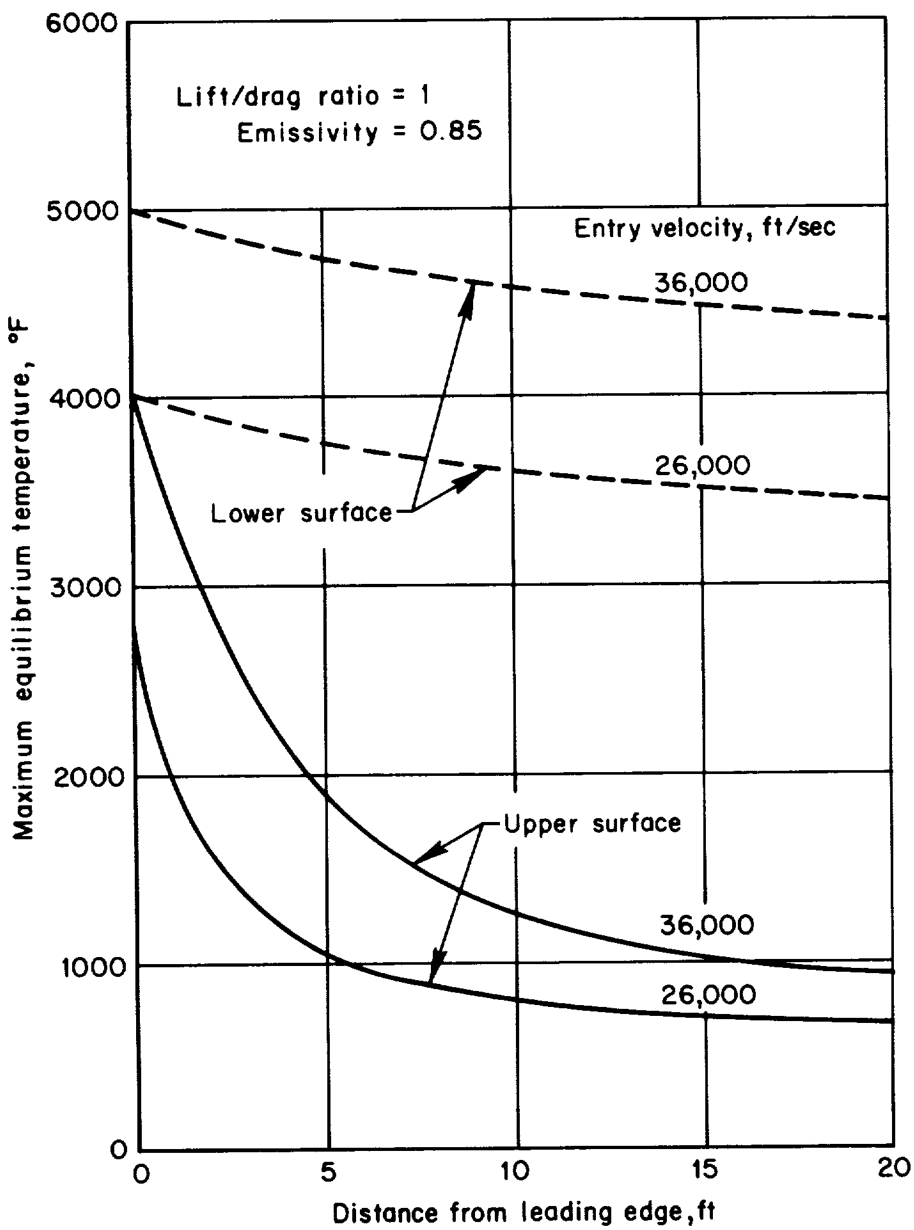

Figure 6.- Maximum surface temperatures for lifting reentry vehicle with purely reradiative thermal protection (from ref. 4).

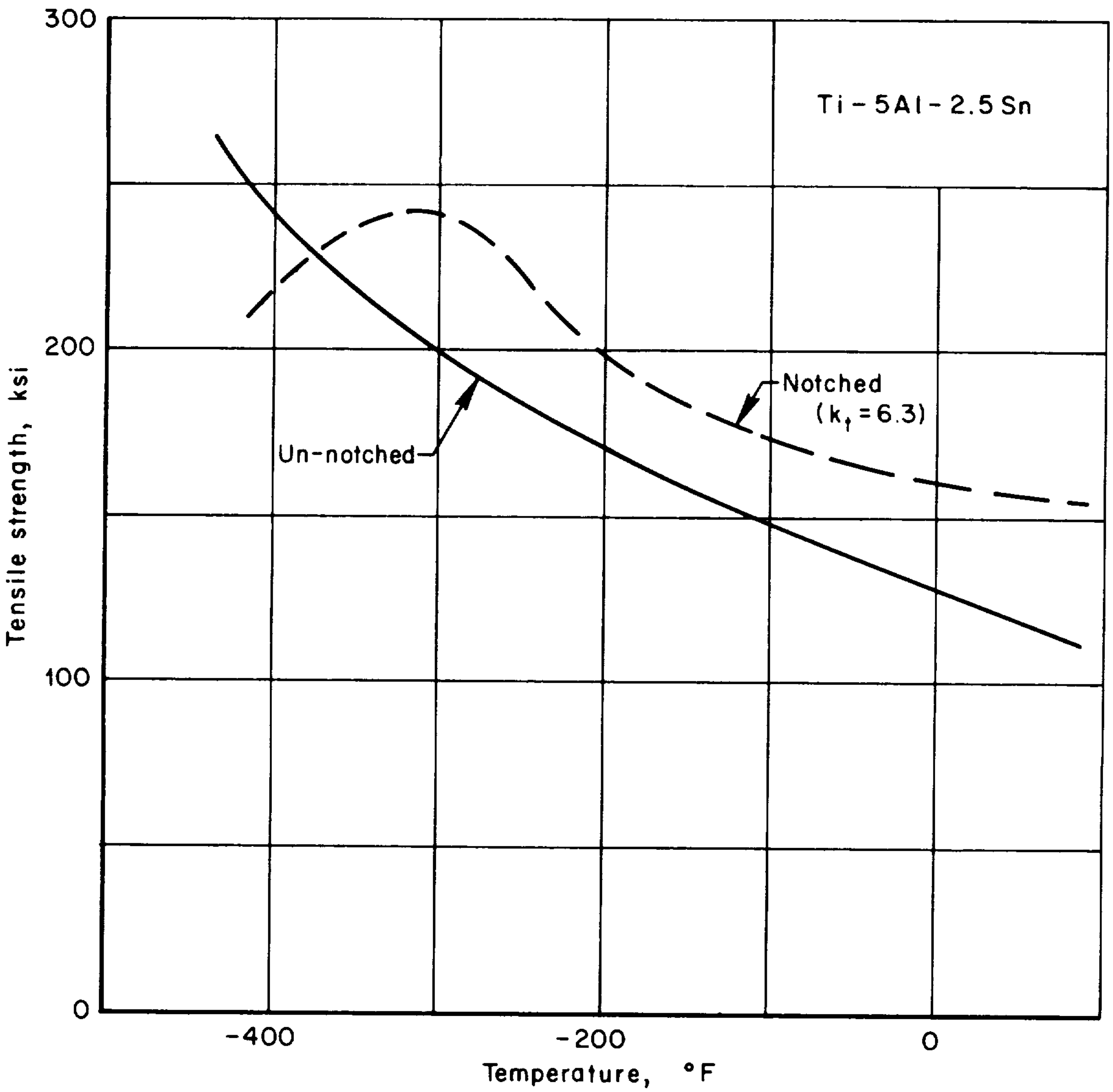

Figure 7.- Strength of alpha titanium at cryogenic temperatures (from ref. 5).

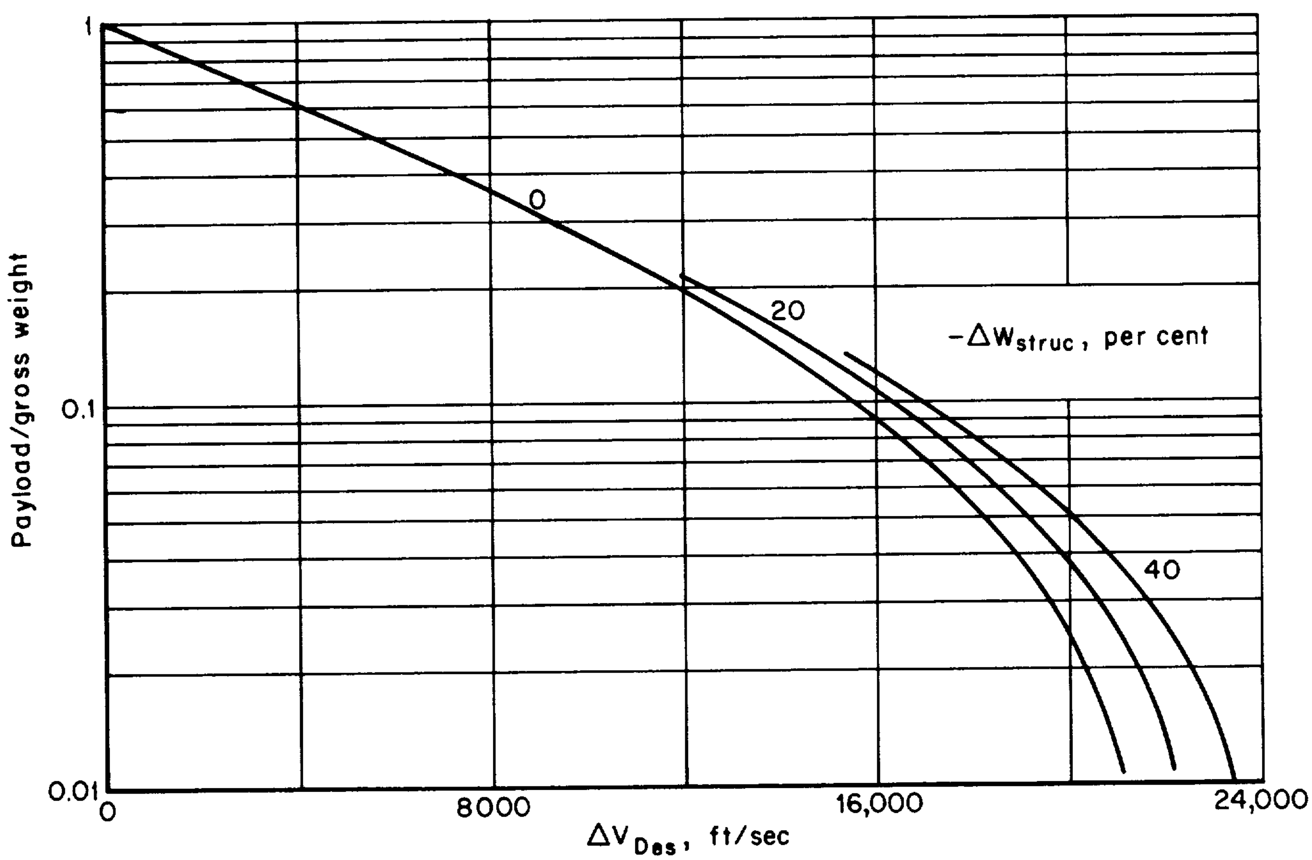

Figure 8.- Performance increases from reduction of structural weight of first stage of typical booster (from ref. 6).

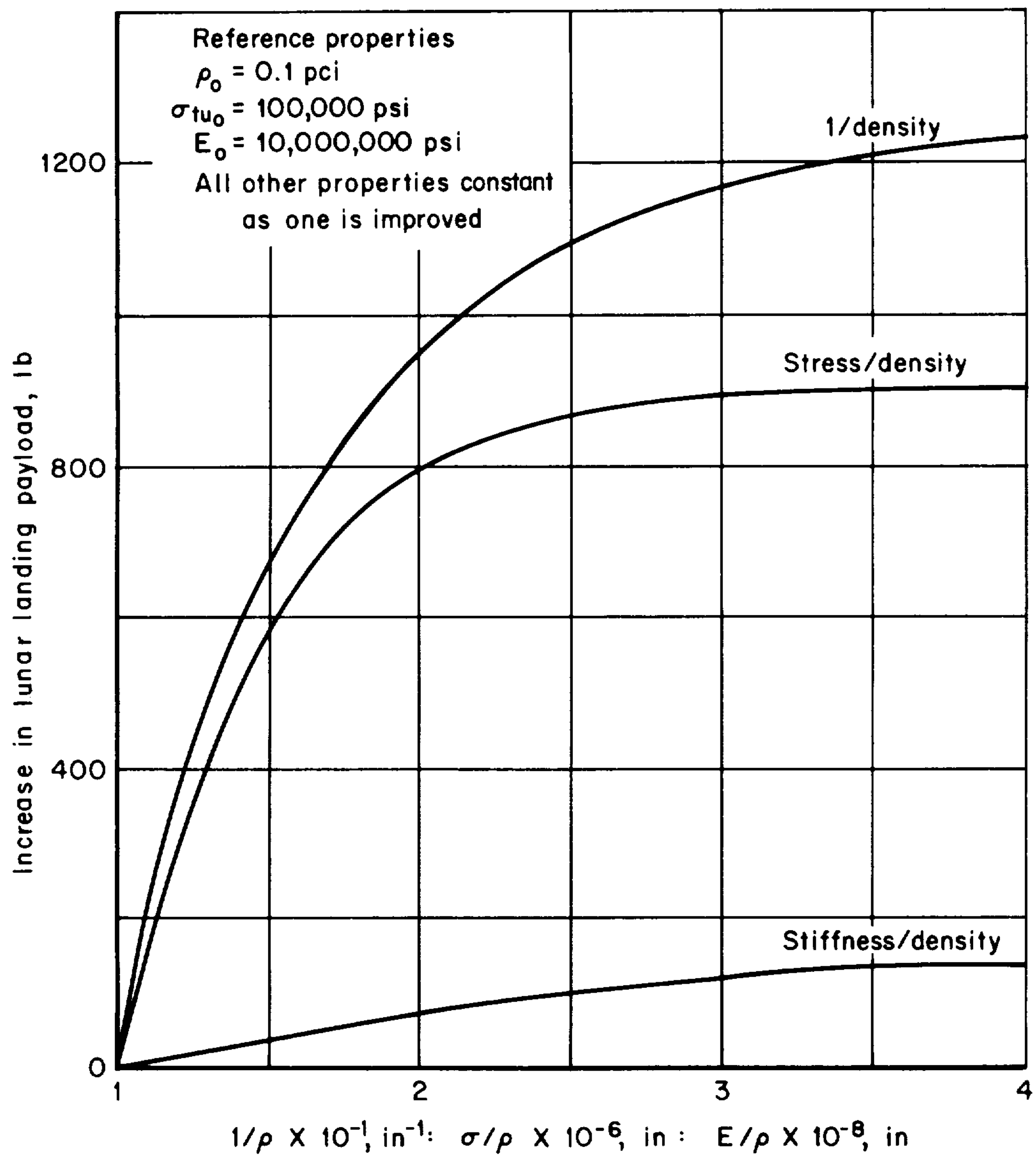

Figure 9.- Increases in payload capability as a function of improvements in material properties of structure for command and service module and lunar lander of reference 7.

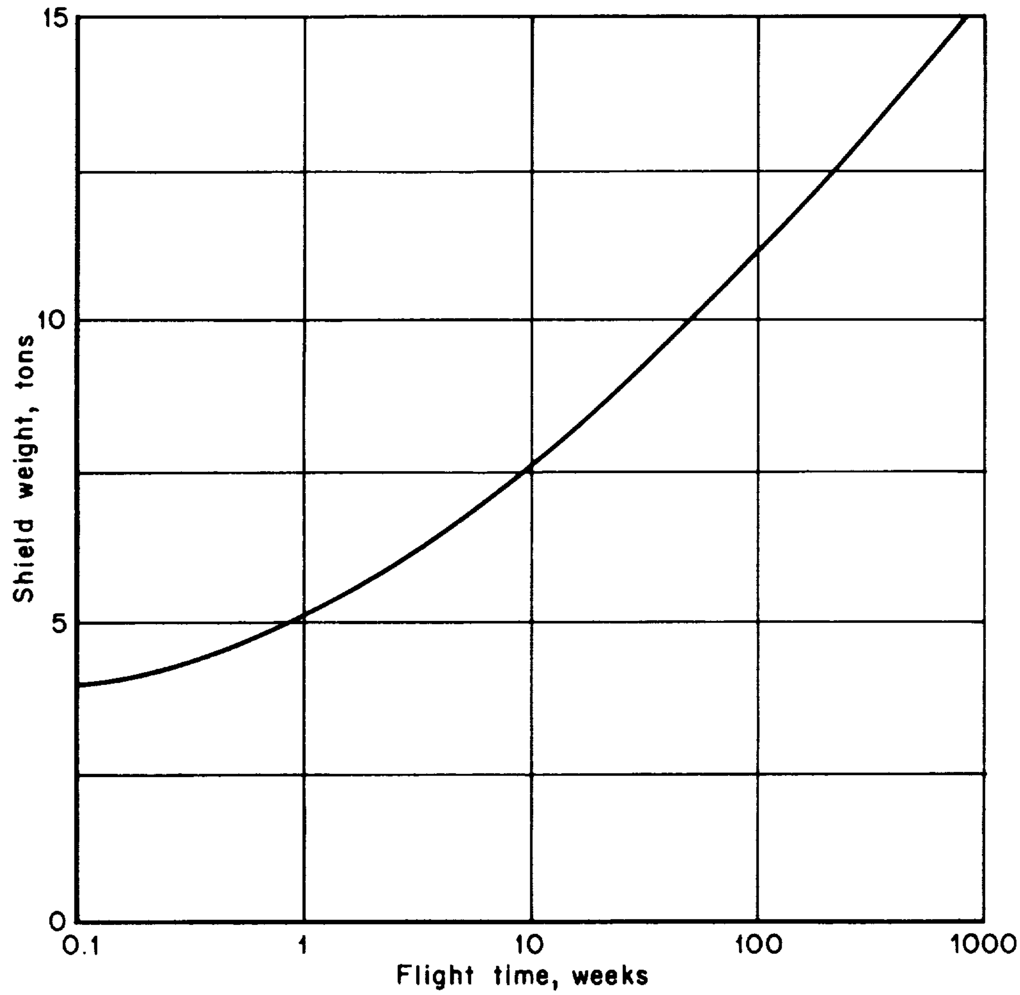

Figure 10.- Weight of radiation shielding required to insure dose less than 100 REM inside 10-foot-diameter space vehicle (ref. 8).

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